3D Broadband Propagation In A Fluctuating Shallow Water Environment

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LONG-TERM GOAL

The long term goal of this project is to provide a numerically efficient and robust acoustic model for the propagation of waves in a three-dimensional fluctuating shallow water environment.

OBJECTIVES

The scientific objectives of this work, as a first step toward the long term goal, are:
1: Develop a new, more efficient 2D propagation model based on the coupled mode method which is more efficient but as accurate as the parabolic equation (PE) model.
2: Use this model to study how signal coherence in the ocean is affected by sound speed fluctuations caused by internal waves.

APPROACH

Coupled mode model:

Coupled mode equations are generally derived from the wave equation by dividing a range dependent waveguide into range independent sections where in each section the wave equation can be solved as a sum of local normal modes [1]. The coupling between modes are expressed as integrals with respect to depth of the local modes and their range derivatives.

The use of the wave equation in deriving the coupled mode equations results in two sets coupling coefficients: one which involves first and one which involves second derivatives of the local modes with respect to range. Computation of the coupling coefficients, particularly the one which involves the second derivative of the modes with respect to range, is impractical and inaccurate at best. It is therefore common to resort to approximations which, among other things, destroy the anti-symmetry of the coupling coefficients [2], [3]. An energy conserving solution requires the coupling coefficients to be anti-symmetric.

Instead of using the wave equation, our approach is to use the equations of motion to derive the coupled mode equations. By this method only one set of coupling coefficient is obtained. What is more important is that these coupling coefficients are simple to compute since they involve the depth derivatives rather than the range derivatives of the local modes. Furthermore, this method guarantees energy conservation since the coupling coefficients obtained this way are anti-symmetric.

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A fluctuating shallow water environment:

Our approach to applying the above coupled mode model to a fluctuating shallow water environment is to use the CTD measurements from the Santa Barbara Channel Experiment. The sound profile is directly obtained from the CTD measurements and standard oceanographic methods are used to model the sound speed fluctuations due to internal waves [4].

Signal coherence:

As a measure of signal coherence we study the correlation between generated data on a vertical line array (VLA) obtained from the above coupled mode model in a fluctuating shallow water environment and replica fields obtained from a conventional normal mode model where it is assumed that the sound speed profile is constant (not fluctuating) in range at its background value. The correlation is given by the output of the linear (Bartlett) processor:

$$C^k(r,z) = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} W_i^*(r,z) R_{ij}^k(r,z) W_j(r,z)}{\sum_{i=1}^{N} W_i^* W_j \sum_{i=1}^{N} R_{ii}^k}$$

In the above W_i are the replica vectors and R_{ij}^k is the data covariance matrix for realization k. Note that C^k is unity for perfect data-replica match.

WORK COMPLETED

The equations of motion were used to derive a set of first order, coupled, ordinary differential equations for the mode amplitudes. A knowledge of the mode amplitudes as function of range is sufficient to compute the acoustic field in a range dependent waveguide. The differential equations for the mode amplitudes are coupled by the coupling coefficient matrix. The coupling coefficients are made up of two terms. A bathymetric term which accounts for mode coupling due changes in bathymetry and a volumetric term which accounts for mode coupling due to sound speed variations in the water column. For sound speed fluctuations due internal waves in a flat waveguide only the latter term contributes.

The data from the Santa Barbara Channel Experiment were used to obtain oceanographic parameters like the sound speed, density and buoyancy profiles as shown in Fig.(1). The internal wave eigenvalue equation was solved for a range of internal wave frequencies and wavenumbers and the internal wave modes were obtained. The internal wave displacements and finally the sound speed fluctuations were computed by assuming that the internal wave amplitudes obeyed the Garrett-Munk spectral model. The sound speed fluctuations computed for a number of realizations at an arbitrary range is shown in Fig.(2). From the sound speed fluctuations as a function of range the coupling coefficients and the mode amplitudes were computed, enabling one to compute the acoustic field anywhere in the ocean waveguide.

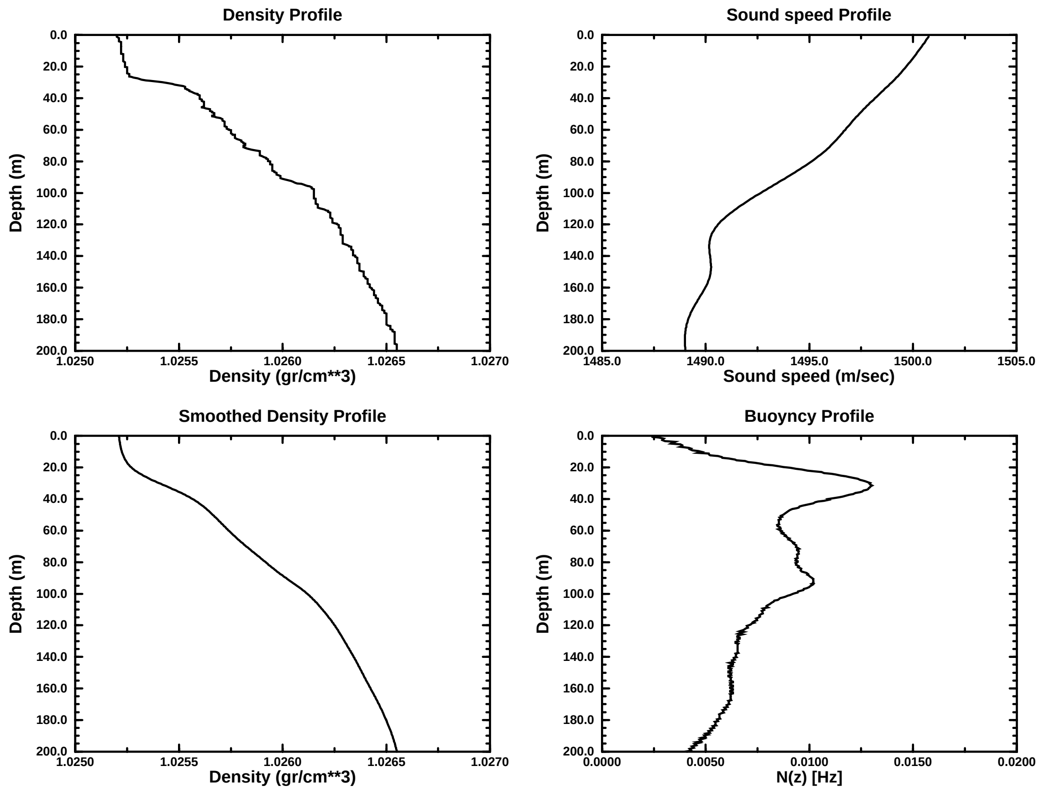

Figure 1: Density, sound speed and buoyancy profiles for the Santa Barbara Channel. The density profile is smoothed in order to get a smooth buoyancy profile.

RESULTS

The Santa Barbara Channel Experiment was conducted in 200 m of water over a flat bottom. To study the signal coherence due to internal waves, the correlation between generated data and replicas was computed. For each realization the above coupled mode model was used to generate data on a 35 element vertical line spanning the whole water column for a number of source locations and frequencies. This array was chosen because experimental data were recorded on a similar array during the CTD measurements. The source was placed at 4, 8 and 16 km and the source frequencies were 125, 250 and 500 Hz. The source depth was kept constant at 60 m. The replicas were computed using a range independent model where it was assumed that the sound speed profile was constant in range at its background value given by Fig.(1). Therefore, any degradation in correlation between data and replica could be associated with a degradation in signal coherence due to internal waves.

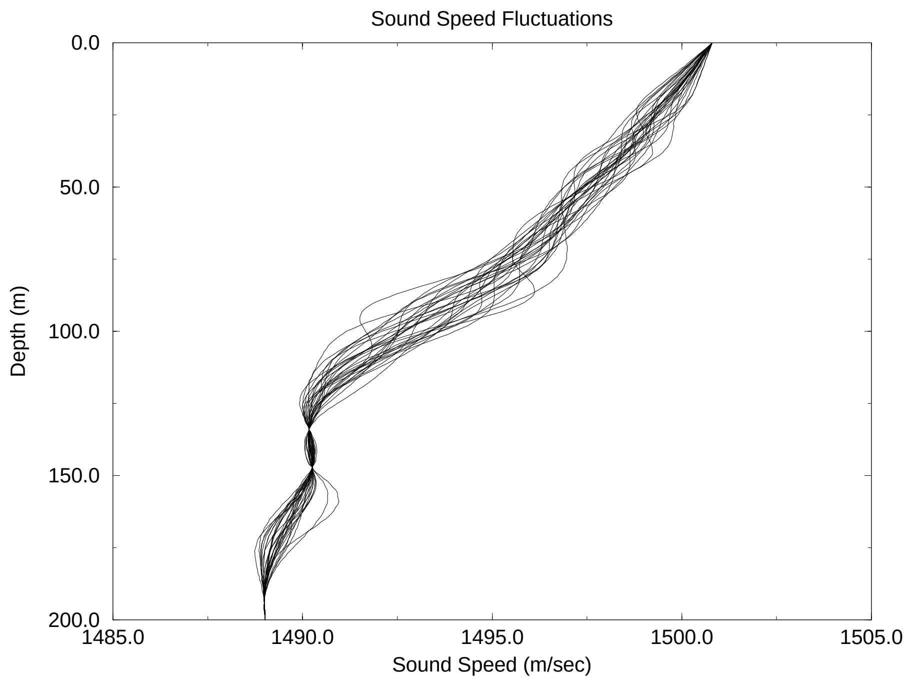

Figure 2: Computed sound speed fluctuations in the Santa Barbara Channel for a number of realizations.

For each of the above source locations and frequencies the correlation was computed for 200 realizations. For each realization a complete range and depth search was performed and the source location, which was associated with the maximum correlation, was determined. The source was located correctly 95 percent of the time. Figure 3 shows the distributions of the correlations. It can be seen that as the source frequency and range increase the mean of the correlations decreases and their variance increases. However, in all cases the correlations are quite high which suggests that for a noise free environments where the sound speed fluctuations are similar to that shown in Fig.(2) signal coherence is not substantially affected by internal waves as a source with source frequency less than 500 Hz can be detected with reasonable certainty as far away as 16 km.

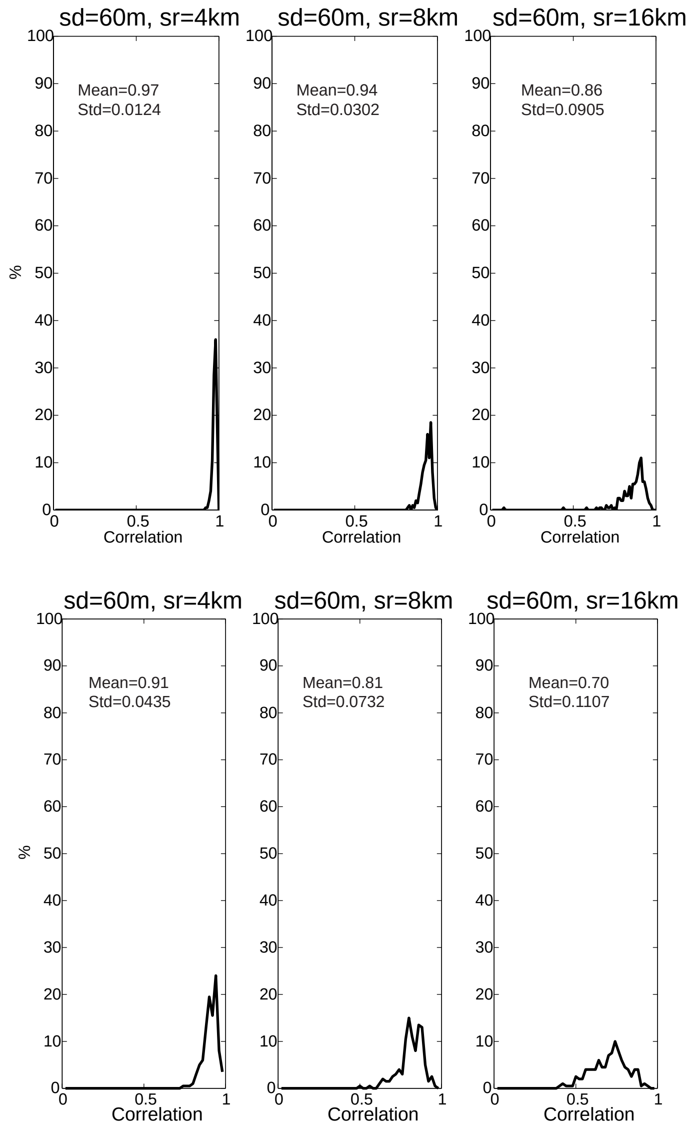

Figure 3: The distribution of correlations. The source frequency in the top panels is 250 Hz and in the bottom panels is 500 Hz. Observe that the distributions become wider and shift to the left for high frequencies and longer ranges.

Our next objective was to see if internal waves had any significant contribution to the signal degradation caused by the source motion. For this purpose, we changed the source range from its original location by increments of 10 m and at each new location averaged the resulting signal covariance matrix with those obtained at previous locations. The replica vectors were computed only for the original source location. As more and more covrainace matrices were averaged, the degradation in correlation increased. We carried out this computation with and without the presence of internal waves and found that the degradation was primarily due to the source motion and did not significantly change in the presence of internal waves.

Finally, we studied how the signal coherence changed as a function of time by letting the internal wave field evolve in time for a period of three hours. We computed the correlations as a function of time for

the above source locations and frequencies. The correlations fluctuated around a mean value which was near 0.85 for short ranges and low frequencies and 0.70 for long ranges and high frequencies.

Based on the results of our simuations in a noise free environment where the sound speed fluctuations are similar to those shown in Fig.(1) internal waves do not substantially degrade signal coherece. Furthermore, this degradation is primarily due to the spatial, not the temporal, variations in the internal wave field.

IMPACT/APPLICATION

The coupled mode model developed under this task can be used in propagation modeling involving bathymetric or volumetric range dependence.

TRANSITIONS

This model is particularly appropriate for use in tomography and generating replica field vectors used in matched field processing (MFP) work sponsored by ONR and DARPA.

RELATED PROJECTS

Under the sponsorship of the Internal Research (IR) program at the SPAWAR Systems Center, San Diego, the above coupled mode method is being extended to model propagation in a range dependent elastic medium.

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